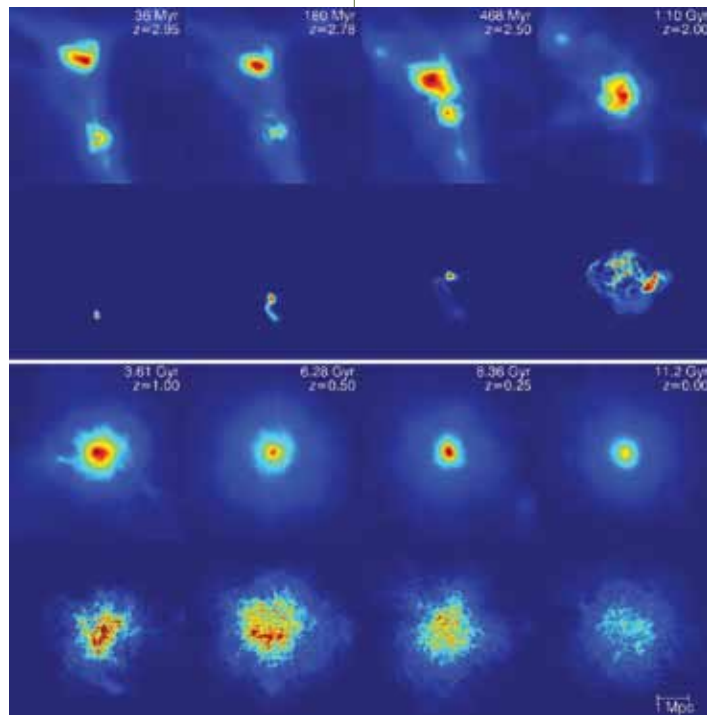


# Origin of Magnetic Fields in Galaxy Clusters

Hao Xu, Hui Li, T-2

**Fig. 1. Snapshots of the projected baryon density (upper rows) and magnetic energy density (lower rows) for different epochs of cluster formation. Each image is 5.71 Mpc (comoving) on a side. Cluster mergers continuously extend the distribution of the magnetic fields and amplify them.**



Galaxy clusters are the largest gravitationally bound objects in the Universe. Each cluster contains as many as thousands of galaxies and large amounts of intergalactic gas known as the intracluster medium (ICM). The detection of large-scale, diffuse radio emissions, called radio halos, and relics in galaxy clusters, as well as other observations, show that the ICM is permeated with cluster-wide micro Gauss ( $\mu\text{G}$ ) magnetic fields [1]. These magnetic fields play a significant role in determining the structure of clusters through processes such as heat transport, which consequently affect

the applicability of clusters as sensitive probes for cosmological parameters [2].

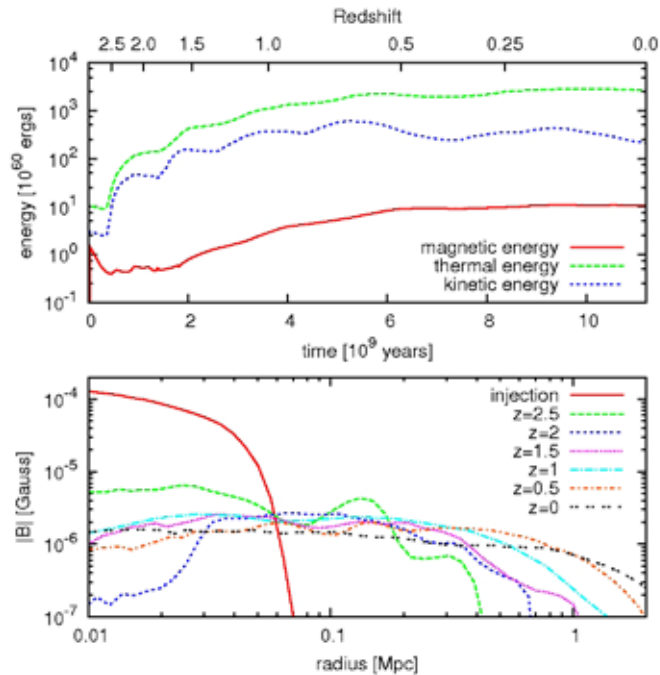
The origin of cluster magnetic fields is still not clear. Two possibilities have been considered promising and have received the most attention: 1) magnetic fields are initially from the outflows of normal or active galaxies, and such fields can be further amplified by cluster turbulence, and 2) very weak proto-galactic seed fields, such as from the Biermann battery effect, are amplified by dynamo processes in clusters.

In recent work, we have made significant progress in addressing this origin problem by showing

that the observed magnetic fields can be obtained by amplifications of magnetic fields that are injected by an active galactic nucleus (AGN) using large-scale cosmological simulations [3]. We used the newly developed ENZO+MHD code, which is a grid-based cosmological Magneto Hydrodynamics (MHD) + N-body code with adaptive mesh refinement (AMR) [4]. This code was developed jointly by the University of California, San Diego and LANL. It uses the AMR algorithm to improve spatial and temporal resolution in regions of interest, such as gravitationally collapsing objects. In this research, we performed a detailed self-consistent simulation of galaxy cluster formation without magnetic fields from redshift  $z = 30$  to  $z = 3$ . Then we restarted the simulation with the magnetic fields injected into the largest halo at that time, using a magnetic tower model [5] to mimic the magnetic fields output from an AGN, and ran the simulation to  $z = 0$ . The magnetic field injection lasts for 36 Myr and the injected magnetic energy is  $\sim 2 \times 10^{60}$  ergs.

The formation of clusters and the evolution of magnetic fields are shown in Fig. 1 as snapshots of projected gas density and magnetic energy density. The injected local magnetic fields are distributed throughout the entire cluster when the cluster is formed by hierarchy mergers. After the injection, the expansion of the injected magnetic fields first forms the density cavities, reminiscent of the jet-lobe structure of an AGN outburst. As the evolution progresses, magnetic fields, which follow the gas motion, are being sheared, twisted, and spread throughout the whole cluster. Judging by the images, this volume-filling process is quite efficient. By  $z = 0.5$ , magnetic fields are already well mixed with the ICM and are distributed quasi-uniformly throughout the whole cluster, except that some high magnetic field regions obviously from compression by merger shocks. At the time when the simulation ends, while the cluster is relaxed, the magnetic fields are quite uniformly distributed.

During the course of the magnetic fields spreading throughout the whole cluster, the total magnetic energy increases significantly. The magnetic energy inside the cluster increases to more than  $10^{61}$  ergs with a 25 times gain (see the top panel of Fig. 2). The spherical averaged radial profiles (bottom panel of Fig. 2) of magnetic field



**Fig. 2.** *Top panel: Temporal evolution of different components of energy inside the virial radius of the cluster. Bottom panel: The spherically averaged radial profile of magnetic field strength. The radius is measured in the proper frame.*

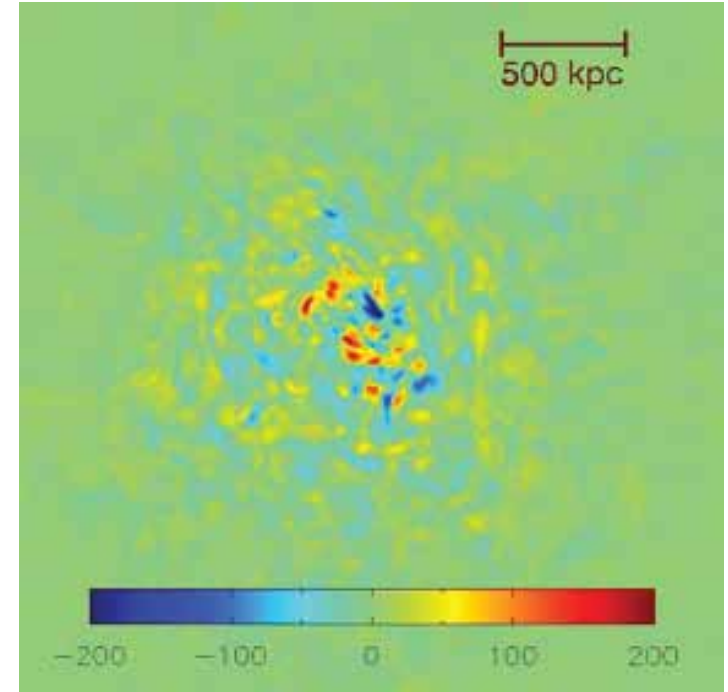
strength at different epochs of the cluster formation show the turbulent diffusion of magnetic fields throughout the cluster, yet maintain their strength via the dynamo process. The strength of magnetic fields at  $z = 0$  is a few  $\mu\text{G}$  at the cluster center and drops slowly with increasing radius to sub- $\mu\text{G}$  at the cluster edge. This radial profile is consistent with the results from observations.

We also computed the synthetic Faraday rotation measurement (FRM) of the cluster, which is the most-used observation for determining the structure of magnetic fields in cosmological objects. The typical value of FRM (Fig. 3) in our simulation is  $\pm 200 \text{ rad m}^{-2}$ , with high values concentrated in the cluster core region. The FRM map not only shows the small-scale variations that are reminiscent of MHD turbulence of the ICM, but also

displays long, narrow filaments. The FRM magnitudes and spatial distributions from our simulation are quite consistent with observations of clusters.

Since AGNs are commonly observed in galaxy clusters, one important implication of our studies is that the magnetic fields from AGNs alone are perhaps enough to provide the initial magnetic fields in the clusters, and the ICM turbulence will spread and amplify the AGN fields to the observed magnetic fields in clusters via a dynamo process. Future radio and X-ray observations, especially the Extend Very Large Array, which is under construction, will provide an unprecedented level of detail of radio sources and magnetic fields in the ICM. Such theoretical and simulation studies will be timely in understanding the observations.

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**Fig. 3.** *Faraday rotation measurement of the ICM of the simulated cluster at  $z = 0$ . The distribution of FRM is consistent with the observed FRM distributions from real clusters.*

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